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A method of fault diagnosis and flight envelop assessment for flight control systems

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Abstract

To improve the controllability of an aircraft in the presence of control surface damage, a method of fault diagnosis and flight envelop assessment is proposed in this paper. Firstly, it is considered that the control surface damage could cause the aerodynamic parameter change, so the damage model is built. Then, based on the recursive least square method, the aerodynamic parameters are identified in online. Finally, based on identification parameters, the online fault diagnosis is processed by remains decision technology, at the same time the flight envelop is assessed accurately. The simulation results show the fault diagnosis and envelop assessment is achieved.

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Keywords: control surface damage; fault diagnosis; flight envelop assessment; the least square method

1. Introduction

The actuators are a key component of flight control systems to keep high controllability performance. The control surface failure will influence the force and moment of the aircraft, so it will influence the flight capability of aircraft. Especially, the flight envelop is changed because of the control surface failure, whereas the wreck will occur over the safety flight envelop. So the failure diagnosis and flight envelop assessment is processed completely, and the result information is provided for a pilot, which is important to improve the flight safety of aircraft.

In recent years, there are some aerodynamic parameter identification and fault diagnosis methods for control surface damages have been proposed[1-6]. From above reference, we can see that this kind of problems has three key focuses: building failure model, parameter identification, and flight envelop Assessment. In this paper, a real-time parameter identification method is introduced to analyze the relation of control surface failure and flight envelops, and fault diagnosis is realized for in the flight control systems. The scheme is demonstrated through simulations applying the flight control system of an aircraft. The simulation results show the failure diagnosis and envelop assessment is achieved.

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2. Problem statement

Damaged surfaces may result in the changes of the aerodynamics coefficients and control effectiveness deficiencies. Typical actuator failures include: Lock-in-place; Float; and Loss of effectiveness. Loss of effectiveness can change the force and moment of the aircraft, and the flight envelop will be reduced. Therefore the identification of the aerodynamic coefficients and the extrapolation of the identified system dynamics are key steps for model the damaged aircraft. In this paper, the wing damage will be considered through changing the wing reference area.

The Non-dimensional aerodynamic force and moment coefficients for an aircraft can be computed from flight measurements and known quantities on the right sides of the formula (1) and (2). For local real-time model over a short time period, the force and moment coefficients computed on the left sides of the formula (2) and (2) [3]:

$$\begin{aligned} C_x &= (1/\bar{q}s)(ma_x - T_x) = C_{x\alpha}\alpha + C_{x\delta e}\delta_e + C_{x0} \\ C_y &= (ma_y)/(\bar{q}s) = C_{y\beta}\beta + C_{x\delta r}\delta_r + C_{y0} \\ C_z &= (1/\bar{q}s)(ma_z - T_z) = C_{z\alpha}\alpha + C_{z\delta e}\delta_e + C_{z0} \end{aligned} \tag{1}$$

$$\begin{aligned} C_l &= (1/\bar{q}sb)(I_x\dot{p} + (I_z - I_y)qr - I_{xz}(pq + \dot{r})) = C_{l\beta}\beta + C_{lp}\frac{pb}{2v} + C_{lr}\frac{rb}{2v} + C_{l\delta a}\delta_a + C_{l\delta_r}\delta_r + C_{l0} \\ C_m &= (1/\bar{q}s\bar{c})(I_y\dot{q} + (I_x - I_z)pr + I_{XZ}(p^2 - r^2) - M_T) = C_{m\alpha}\alpha + C_{mq}\frac{q\bar{c}}{2v} + C_{m\delta e}\delta_e + C_{m0} \\ C_n &= (1/\bar{q}sb)(I_z\dot{r} + (I_y - I_x)pq - I_{xz}(\dot{p} - qr)) = C_{n\beta}\beta + C_{np}\frac{pb}{2v} + C_{nr}\frac{rb}{2v} + C_{n\delta a}\delta_a + C_{n\delta r}\delta_r + C_{n0} \end{aligned} \tag{2}$$

Here, $\bar{q}$ is dynamic pressure, α and β are angle of attack and sideslip angle. b and S are wing span and wing reference area. I_x, I_y, I_z, and I_{xz} are mass moments of inertia. C_l, C_m, and C_n are body-axis non-dimensional aerodynamic moment coefficients. δ_e, δ_a and δ_r are elevator, aileron, and rudder deflections. p, q, and r are body-axis roll, pitch, and yaw rates. C_x 、 C_y 、 C_z are body-axis non-dimensional aerodynamic force coefficients. a_x 、 a_y 、 a_z are body-axis translational accelerometer measurements.

3. Fault diagnosis and flight envelope assessment

Considered the characteristic of control surface damage in flight control systems, a scheme of real-time fault diagnosis and envelop assessment is introduced (illustrated in Fig.1).

A summary of the real-time fault diagnosis and envelop assessment approach is outlined in the following steps:

Step 1: Based on the input and output data, a real-time identification model is set up, which the changes of aerodynamic coefficients are identified by a recursive least square method using onboard sensor measurement;

Step 2: Using the information of identification parameters, the remains is produce by compared the nominal aerodynamic coefficient, and real-time fault diagnosis is achieved by designed threshold;

Step 3: The flight envelope estimation is continuously updated and improved based on the aerodynamic coefficients.

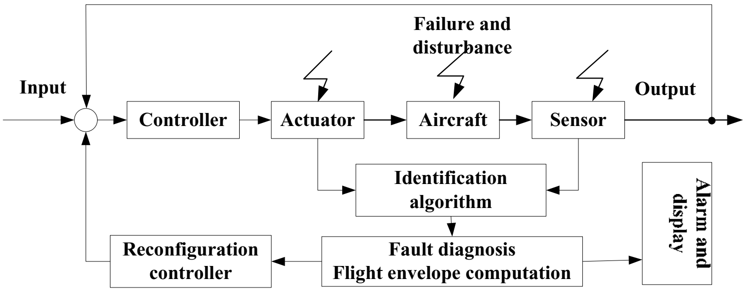

Figure 1. An overview of real-time fault diagnosis and envelop assessment

3.1. aerodynamic coefficients identification

In the context of parameter identification application to aircraft, regression refers to a statistical technique for modeling and investigating relationships among measured variables. For aerodynamic model in formula (1) and (2), the linear measurement equation was expressed as[4-6]

$$z = X\theta + \xi \quad (3)$$

Here, for example, using the pitching moment equation, $z = [C_m(1), C_m(2) \cdots C_m(N)]^{\mathrm{T}}$, $\theta = [C_{m\alpha}, C_{mq}, C_{m\delta_e}, C_{m0}]^{\mathrm{T}}$, $X = [\alpha, \frac{q\bar{c}}{2v}, \delta_e, 1]$, $\xi = [\xi(1), \xi(2), \cdots \xi(N)]^{\mathrm{T}}$.

The least squares solution based on measurements followed from minimization of the cost function

$$J(\theta) = \frac{1}{2}\sum_{i=1}^{k}[z(i) - X^{\mathrm{T}}(i)\theta]^2 \quad (4)$$

To realize real-time identification, the algorithms will use recursive mode. Therefore, the recursive least squares estimate can be put as the following equations:

$$\begin{aligned} \bar{\theta}(k+1) &= \hat{\theta}(k) + K(k+1)[z(k+1) - x^{\mathrm{T}}(k+1)\bar{\theta}(k)] \\ K(k+1) &= D(k)x(k+1)[1 + x^{\mathrm{T}}(k+1)D(k)x(k+1)]^{-1} \quad (5) \\ D(k+1) &= [D(k) - K(k+1)x^{\mathrm{T}}(k+1)D(k)] \end{aligned}$$

Here, $\bar{\theta}$ is the estimate of the θ. To improve the estimate precision and speediness, the starting value $\bar{\theta}(0)$ and $D(0)$ must be designed before the algorithms is ran.

Based on above identification algorithms, the aerodynamic coefficients are identified by used formula (1) and (2) equations and measurements. The impulsive signal of the least squares estimate is input by adding the nominal signal of the control surface deflections.

3.2. fault diagnosis

Based on identification result, the control surface damages are detected online by remains decision technology. To improve the real-time, the threshold logic technology is used. Detection threshold criterion is designed as follows:

$$\left|\hat{y}(t) - y(t)\right| \geq 5\sigma + \varepsilon \quad (6)$$

Here, σ is measurement noise standard deviation, ξ denotes the least squares estimate err.

At the same time, to diagnose and distinguish failures, the control surface loss efficiency is analyzed by using the following formulae:

$$k = \frac{\bar{C} - C}{C} \times 100\% \quad (7)$$

Here, $\bar{C}$ is aerodynamic coefficients identification value, C is ordinary aerodynamic coefficients which is get by wind tunnel experiment.

3.3. flight envelop assessment

The flight envelope of an aircraft represents the ranges of altitudes and speeds over which the aircraft may operate. This envelope may be drawn as a series of constraining curves on the altitude-Mach number plane, which depends on the propulsion considerations or aerodynamic coefficients [2]. According to parameter identification result, the aerodynamic coefficients are got in level flight condition. And then the flight envelope can be assessed.

According to the level flight aerodynamic characteristic of aircraft, the maximum speed attainable by the aircraft depends on the maximum engine thrust, as well as the wing area and the minimum attainable drag coefficient. This may be expressed as:

$$v_{\max} = \sqrt{\frac{2T_{\max}}{\rho(H) C_{x\min} S}} \quad (8)$$

Here $v_{\max}$ is the maximum possible air speed, $T_{\max}$ is the maximum thrust, $\rho(H)$ is the density of air, $C_{x\min}$ is the minimum drag coefficient.

Similarly, the stall speed may be calculated as:

$$v_{\min} = \sqrt{\frac{2G}{\rho(H) C_{z\max} S}} \quad (9)$$

Here G is the weight of the aircraft, $C_{z\max}$ is the maximum lift coefficient, and $v_{\min}$ is the stall speed.

When the wing damages, the parameter about $C_{x\min}$, $C_{z\max}$ and S will be changed so that the flight envelope will be influenced. Because the flight envelop is computed online which it is only get the value of current time, the flight envelope at a different flight condition based on the estimation at current and past conditions. The flight envelope must consist of a real-time flight envelope assessment and an extended flight envelope that is used by evaluating offline.

4. simulation analysis

In this paper, the flight condition is a straight level flight condition at 0~11000 meter altitude and 0.1~0.8 mach. The sampling period is chosen to be 0.01 second, and simulation time is 50 second. According to level flight condition, a parameter identification model is set by using the proposed method.

The failure scenarios for an aircraft are as follows: left wing loss 25% and 50% separately, the inboard flap loss, and outboard hole 10%. For the case in the left wing loss 50%, the flight envelop is shown in Fig.2, and the residuals computed from the aerodynamic coefficients identification and the reality value are shown in Fig.3. From the figure 3, when the failure occurs, the residuals exceed the threshold criterion immediately, which shows the fault diagnosis is archived. At the same time, the loss efficiency can be computed by using formula (7).

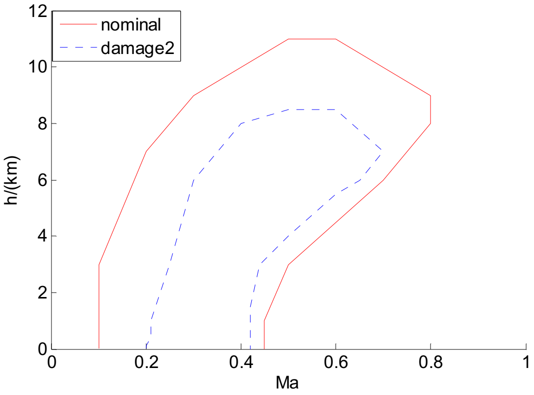

Figure 2. Flight envelop assessment of the left wing loss 50%

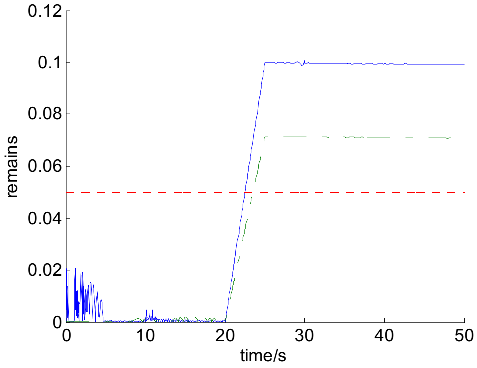

Figure 3. The remains decision of the left wing loss 50%

From the simulation results, the following considerations can be drawn. Firstly, the wing damage will influence the stall speed and maximum level flight speed so that the flight envelop will be changed. Secondly, because the damaged wing influence the life coefficient more than the drag coefficient, the left flight envelop curves will be shrank more than the right. Thirdly, the failure diagnosis results depend on the parameter identification precision. Finally, in this paper, to research the key problem, the wing damage is considered only, which the other damage will be dealt with the same way.

5. Conclusion

The fault diagnosis and the envelop assessment results will provide the information for a pilot so that the envelop protection and reconfiguration control will be realized. In this paper, the wing damage is researched deeply. The failure model is build to identify the aerodynamic coefficients by using recursive least squares estimate. The failure diagnosis and flight envelop assessment is achieved. The proposed algorithm is satisfying from the simulation results, which widens the research scope of fault-tolerant flight control systems.

Acknowledgements

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